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Spatio-temporal supply–demand of surface water for agroforestry planning in saline landscape of the lower Amudarya Basin

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ABSTRACT

Global warming is predicted to increase water scarcity in many drylands worldwide. In Central Asia, one of the most intensively irrigated dryland agricultural regions, climate change is likely to exacerbate the regional water supply–demand gaps, particularly in downstream areas. The withdrawal of degraded, highly salinized croplands from irrigated farming in favor of tree plantations that effectively utilize saline groundwater may contribute to irrigation water saving, which can generate valuable ecosystem services and provide rural income opportunities. To facilitate the spatial planning of afforestation in the lower Amudarya region, we developed a hydrological algorithm to map the spatio-temporal pattern of water supply–demand. The resulting map, based on seven-year continuous data of cropping pattern and corresponding irrigation dynamics, rainfall, and evapotranspiration at 250 m resolution, revealed the overly irrigated areas from which excess water can be redistributed to water-stressed areas. Furthermore, combining this information with spatial data on marginally productive croplands and with water requirement of tree plantations showed that 67% of these croplands are characterized by water availability sufficient for the introduction of salt-tolerant tree species. The algorithm developed is of potential use for defining the feasibility of introducing alternative (tree) crops with known growth and water use characteristics.

1. Introduction

Irrigated agriculture in the Aral Sea Basin (ASB) utilizes more than 90% of the water resources and generates approximately 30% of the gross domestic product (GDP), providing employment to more than 60% of the population (Eurasian Development Bank, 2009). The agricultural water demand is fulfilled mainly by supplies from the Amudarya and Syrdarya Rivers, which are tributaries of the Aral Sea. Decades of intensive irrigation and inefficient drainage have resulted in the desiccation of the Aral Sea (Micklin, 2016) and rising groundwater tables in the irrigated areas (Ikramov, 2004). Consequently, between 12% and 95% of irrigated croplands has become salinized, particularly in the downstream reaches (Dukhovny et al., 2002). About 20% of cotton yields in the ASB have been lost because of salinity, resulting in financial losses of more than US$ 200 million per year (CISEAU, 2006). Moreover, climate change predictions for the ASB underline temperature increases of 3°–4 °C. The increase in annual temperatures have triggered an increase in the potential evapotranspiration in Central Asia (Lioubimtseva and Henebry, 2009), which is likely to cause 30% further reduction of crop yields, leading to adverse socio-economic impacts (Parry et al., 2007).

Copious research in the ASB highlight the necessity of increasing the efficiency of irrigation water use under conditions of rising evapotranspiration, precarious annual water supplies, and salt load (Varis, 2014), particularly in the heavily affected downstream areas of the Amudarya and Syrdarya Basins (Awan et al., 2011a; Conrad et al., 2013; Tischbein et al., 2013). The withdrawal of highly saline, marginally productive lands from irrigated cropping in favor of planting salt-tolerant, multi-purpose tree species has been proposed to increase the efficiency of water resources management in the lower Amudarya (Khamzina, 2006). The efficient use of saline groundwater by trees minimizes their need for irrigation to only 10%–30% of the crop irrigation requirements (Khamzina et al., 2009). Thus, the afforestation of degraded croplands contributes to the saving of irrigation water that can be diverted to productive cropland areas, allowing the cultivation of water-intensive commercial crops while an array of tree-based

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products could increase water productivity (Djanibekov and Khamzina, 2016). However, annual variability in the water supply jeopardizes the success of afforestation, as evidenced by the poor survival rate of newly planted tree seedlings on cropland with a deeper groundwater table (Schachtsiek et al., 2014). These risks require thorough consideration of the hydrological conditions when selecting sites for afforestation in drylands, particularly in saline areas (Jackson et al., 2005; Ma et al., 2009).

On the basis of recently developed long-term geographic information system (GIS) databases and advancements in remote sensing applications in the downstream ASB (e.g., Conrad et al., 2013), a hydrological algorithm can be designed to aid regional land planners in water management and afforestation efforts. In this context, spatially explicit information on the regional water balance is essential for revealing the mismatch between the irrigation water supply and demand and therefore the areas characterized by water shortage or excess. The excess water from overly irrigated land can be redistributed to water-stressed areas, which would contribute to enhanced regional water use efficiency. Furthermore, the spatial data on water availability in poorly productive croplands (Fritsch et al., 2014) can guide land remediation efforts by revealing degraded croplands with water supplies that are still sufficient for establishing the aforementioned tree plantations.

The integration of multi-source data with different spatial and temporal resolution and that based on unrelated data acquisition designs in a hydrological modeling framework remains a challenge; therefore, applications in irrigated drylands have been limited, particularly in the ASB. For example, Deus et al. (2013) used a spatially distributed conceptual hydrological model driven by remote sensing data to study the spatial and temporal variability of water balance parameters within the Lake Manyara catchment in northern Tanzania. Chehbouni et al. (2008) conducted hydrological modeling for water balance estimation by using inputs derived from remote sensing for the Tensift Basin in central Morocco. The modeling applications for water balance estimation are often restricted by insufficient observed data needed for model calibration, such as water discharge (Li et al., 2009). Nevertheless, Khalaf and Donoghue (2012) were able to adequately estimate spatial groundwater recharge based on hydrological parameters such as land cover, evapotranspiration, precipitation, and a digital elevation model, which were derived solely from remote sensing imagery combined with hydrogeological data in a GIS model on a pixel-by-pixel basis. Irrigation inputs were not considered in this novel approach, but are essential for water balance estimations in the irrigated areas of the ASB.

The objectives of the present study, which focuses on the Khorezm region in the lower Amudarya reaches of the ASB, are (i) to develop a hydrological algorithm for mapping water availability based on the evaluation of a spatially explicit regional water balance that considers irrigation inputs, and (ii) to identify potential sites for afforestation by revealing degraded croplands with sufficient surface water available for tree plantations.

2. Study area

The study region in Khorezm, located between 60.05° and 61.39°E and 41.13°–42.02°N in the lower Amudarya Basin (Fig. 1), covers an area of 3971 km^2 bordered by the Karakum and Kyzylkum Deserts to the south, southwest, and west and by the Amudarya River to the northeast. This region experiences an extremely continental arid climate characterized by very hot summers and cold winters, an average annual rainfall of about 100 mm, and an annual potential evapotranspiration of 1400–1600 mm (Awan et al., 2011a). The topography shows a moderate elevation gradient ranging from 132 m to 77 m a.s.l. from southeast to northwest. The hydraulic gradient in the uppermost aquifer floor is low, resulting in reduced lateral groundwater flows (Ibrakhimov et al., 2007).

The economy of Khorezm depends strongly on irrigated agriculture dominated by the cultivation of cotton, winter wheat, and rice (Djanibekov and Khamzina, 2016). The water is supplied by the Amudarya River and the Tuyamuyun Reservoir via six major water inlet structures and is distributed through an extensive network of open, non-lined channels (Conrad et al., 2013). The crop irrigation is implemented by basin and furrow methods. A significant share of water, 25%–30% of the annual consumption, is used for salt leaching in late February–March prior to the seeding of cotton (Ibrakhimov et al., 2007). Drainage networks collect and transport the leached effluent outside the cropland area to manage the rising groundwater tables and to prevent soil salinization. These drainage practices are only modestly effective given the high water inputs via irrigation losses and leaching into the groundwater in addition to outlet problems and insufficient capacity of the drainage canals in terms of depth and spacing, which is exacerbated by poor maintenance of the infrastructure (Awan et al., 2011a). In consequence, elevated groundwater tables and soil salinity persist owing to low leaching effectiveness and rapid salt accumulation through capillary rise (Ibrakhimov et al., 2007). Farmlands located at the lower reaches of the irrigation network are usually most affected by an insufficient and ill-timed water supply (Olimjanov and Mamarasulov, 2006; Conrad et al., 2007) and consequently a higher salt load (Ibrakhimov et al., 2007).

Since the Soviet period, the irrigation and leaching requirements in the ASB have been determined according to *hydro-module zones*, which are geographical locations differentiated by climatic conditions, soil texture, and groundwater levels. The Khorezm region belongs to hydro-module zones VII, VIII, and IX, which are typified by groundwater levels of 1–2 m below the soil surface. (UzNIIKh, 1992; OblSelVodKhoz, 2004).

3. Materials and methods

The identification of sites that are most likely to ensure successful establishment of tree plantations of salt-tolerant tree species *Elaeagnus angustifolia* L., *Populus euphratica* Oliv., and *Ulmus pumila* L. (Khamzina, 2006) followed a step-wise procedure (Fig. 2). The overall assessment focused on the delineation of cropland areas characterized by different levels of marginality for cropping (Fritsch et al., 2014) and that having water supplies sufficient for satisfying the initial irrigation demand of afforestation during the first year after tree planting (Khamzina et al., 2009).

3.1. Methodological approach in determining site suitability for afforestation

The first step in developing the spatial tool to aid afforestation efforts in the Khorezm region focused on the generation of basic maps of mean monthly rainfall, irrigation, and actual evapotranspiration (AET). The spatial resolution, given by the pixel size of the Moderate Resolution Imaging Spectroradiometer (MODIS) input data, was set to 250 m × 250 m. The maps were produced at monthly time steps for seven consecutive seasons of crop growing from April to October in 2003–2009.

In particular, the initial irrigation demand of trees concerns available water for irrigating the newly planted seedlings at the beginning of a growing season, when farmers most frequently face water shortages. The next crucial point in ensuring the irrigation supply is the mid-season point in July, when the evapotranspiration and water demand peak while juvenile trees are not yet able to effectively utilize the groundwater (Khamzina, 2006). The irrigation demand of tree plantations was considered as a fraction of the mean monthly reference evapotranspiration (ET_{ref}) (Allen, 1998) and estimated as 15% of ET_{ref} (Khamzina et al., 2009; Schachtsiek et al., 2014) for April and July of each year between 2003 and 2009 (Table 1).

The mean monthly rainfall amounts were added to the mean monthly irrigation and leaching water amounts, which resulted in

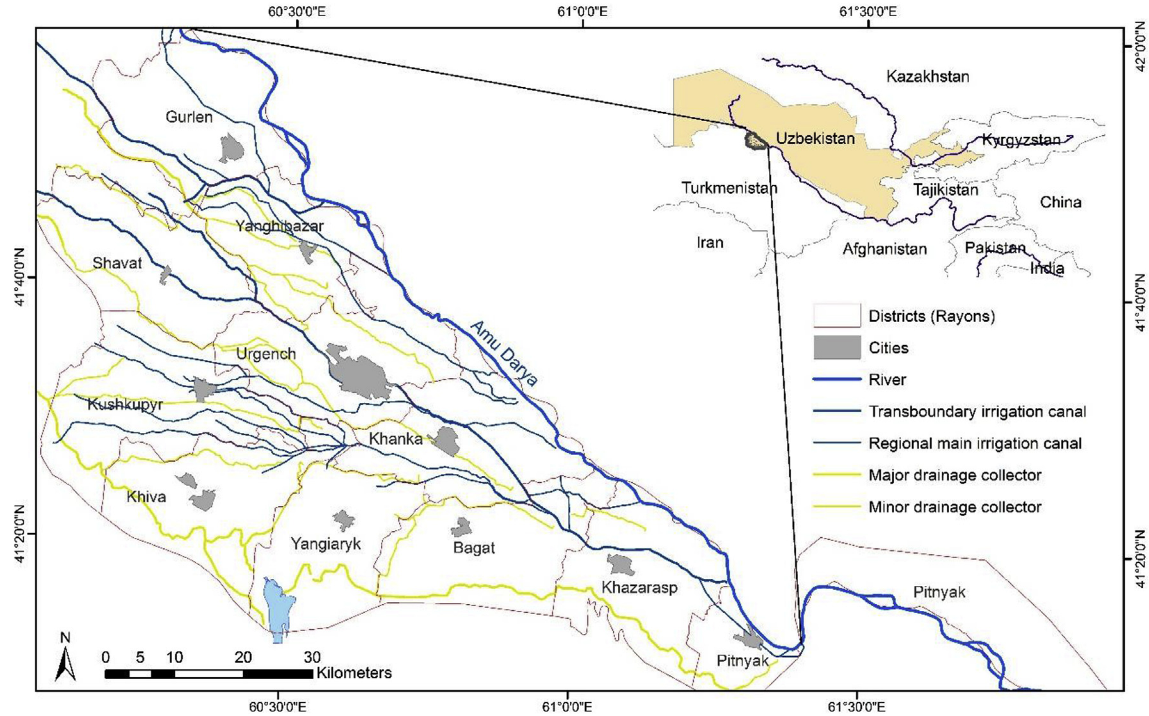

Fig. 1. Location and main irrigation and drainage collector network of the Khorezm region in northern Uzbekistan, lower Amudarya River Basin (Source: GIS lab Khorezm).

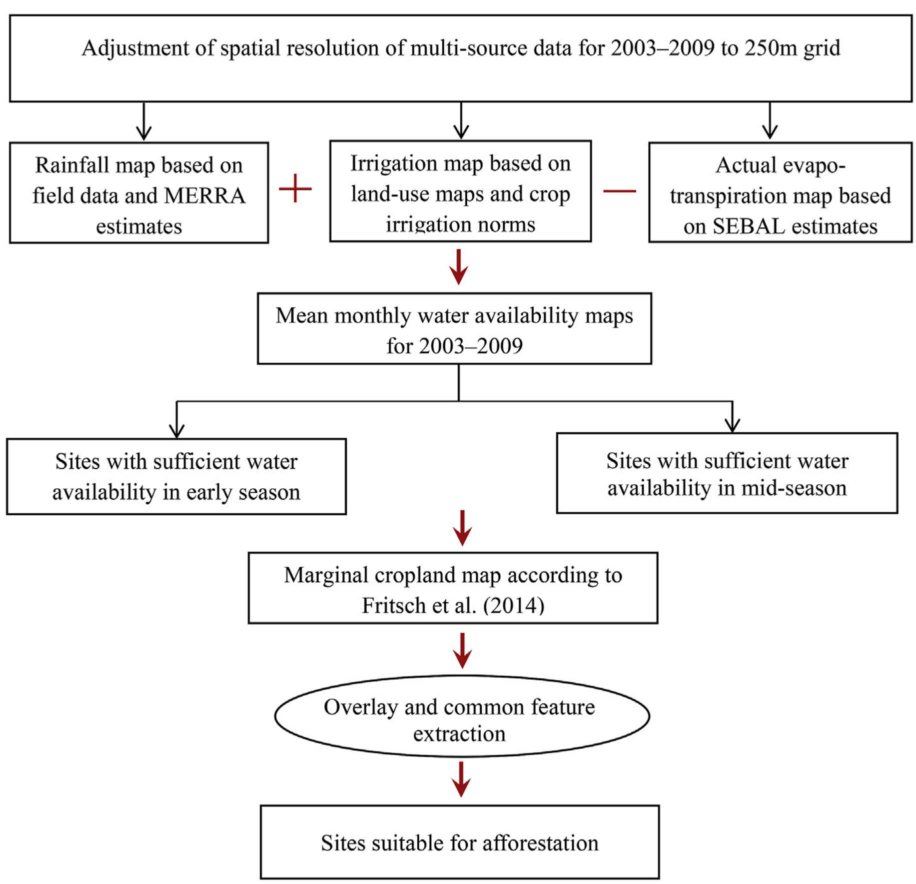

Fig. 2. Workflow for elaboration of the spatially distributed monthly water balance maps and the analysis of site suitability for afforestation.

Table 1
Initial irrigation demand of tree plantations (mm) in the beginning (April) and middle (July) based on 15% of monthly reference evapotranspiration of the 2003–2009 growing seasons.

Year/month	2003	2004	2005	2006	2007	2008	2009	Average
April	18.2	18.0	22.5	21.4	18.4	16.3	11.4	18.0
July	34.5	32.2	34.8	35.2	32.3	26.5	23.4	31.3

monthly water gains per pixel (i.e., mean amounts of water received monthly). Total and effective precipitation were not differentiated owing to scarce rainfall. Next, the AET values were subtracted from their corresponding water gain values, resulting in mean monthly water balances. Because of the limited rainfall, which is dispersed over months, the flat topography in Khorezm, and bunds surrounding the irrigated fields (Ibrakhimov et al., 2007), the surface runoff is negligible as a water balance component and was therefore not considered. The potential groundwater contribution to the water gain could not be quantified owing to the lack of spatial information for estimating the capillary rise. The mean monthly water balance maps of April and July in 2003–2009 were overlaid with a marginal cropland map developed by Fritsch et al. (2014). As a result, marginal cropland areas with > 18 mm and > 31.3 mm of available water per pixel in April and July, respectively (Table 1), were identified as the most water secure areas for tree planting.

3.2. Data review and analysis

3.2.1. Rainfall

Data from five micro-meteorological stations throughout Khorezm formed the basis for capturing the spatial variability in rainfall (Fig. 3a). Three of the stations (Khiva, Tuyamuyun, and Urgench) provided actual ground-based measurements of rainfall and other meteorological parameters. Two stations provided rainfall observations extracted only from 0.5° × 0.6° interpolated grid cells of Modern Era-Retrospective Analysis for Research and Applications (MERRA), which combines satellite and ground-based interpolated estimates. One of these five

Table 2
Percentage shares of hydro-module zones in the administrative districts of the Khorezm region, Uzbekistan.

Administrative district of Khorezm (% of total area)	Hydro-module zones		
	VII	VIII	IX
Bagat	43	19	38
Gurlen	32	32	36
Kushkupir	18	37	45
Urgench	56	13	31
Khazarasp	66	17	17
Khanka	47	27	25
Khiva	27	23	50
Shavat	9	31	60
Yangiarik	24	31	45
Yangibazar	43	20	37
Total	37	25	38

Note: All hydro-module zones are typified by groundwater levels of 1–2 m below the soil surface. Hydro-module VII is characterized by sandy and sandy–loamy soils of thin and intermediate layer thickness; hydro-module VIII has loamy soils of light and moderate textures that become lighter with increasing depth; and hydro-module IX includes heavy loamy and loamy soil (UzNIIKh, 1992; OblSelVodKhoz, 2004).

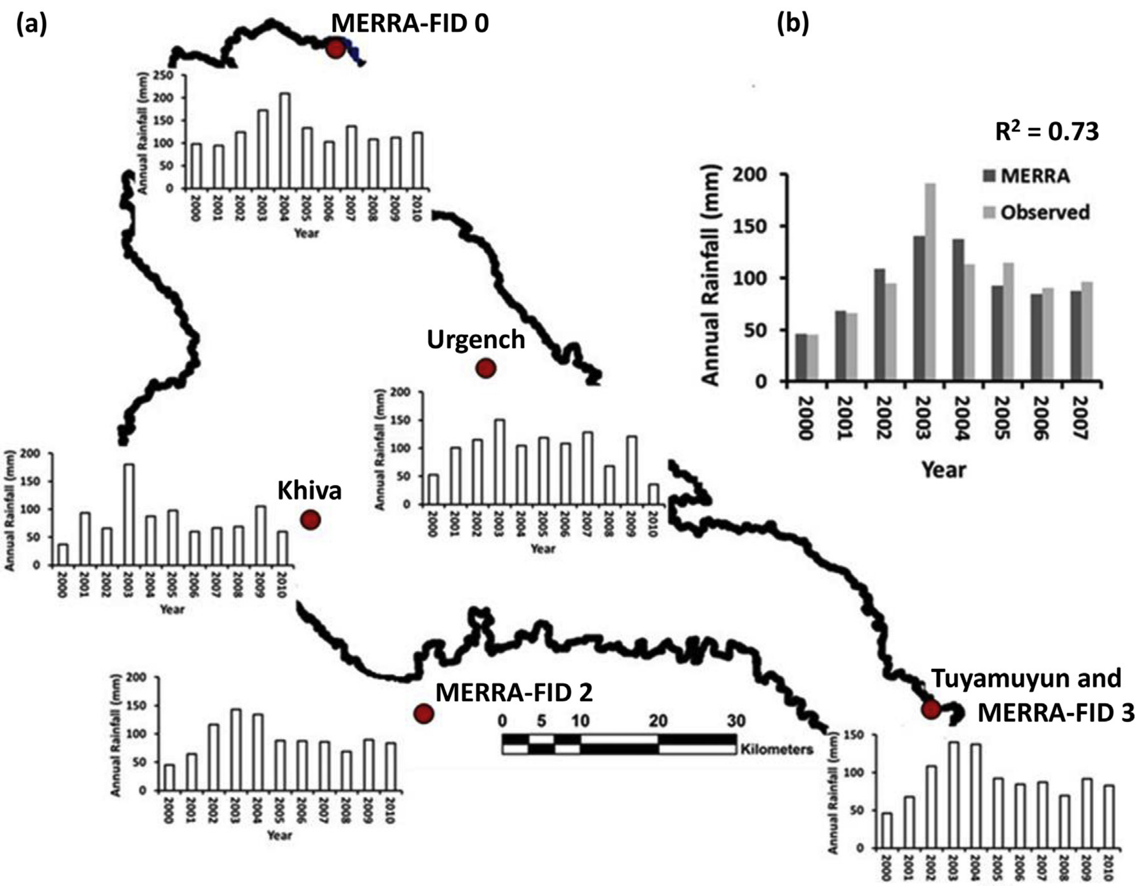

Fig. 3. Spatial distribution of annual precipitation recorded at five locations during 2000–2010 (a) and comparison between values observed by the Tuyamuyun station and estimates by MERRA-FID 3 during 2000–2007 (b) in the Khorezm region, Uzbekistan.

Table 3
Crop water requirements (m^3 ha^{-1}) according to hydro-module zones, and actual water application requirements considering the irrigation network efficiency of 63% in Khorezm, Uzbekistan.

Crop type	Crop water requirement according to hydro-module zone			Average	Actual water application requirement
	VII	VIII	IX		
Cotton	6400	4900	5300	5533	8853
Wheat	4000	3200	3600	3600	5760
Rice	26200	26200	26200	26200	41920
Other	5900	5200	5700	5600	8960

Notes: All hydro-module zones are typified by groundwater levels of 1–2 m below the soil surface. Hydro-module VII is characterized by sandy and sandy–loamy soils of thin and intermediate layer thickness; hydro-module VIII has loamy soils of light and moderate textures that become lighter with increasing depth; and hydro-module IX includes heavy loamy and loamy soil (UzNIIKh, 1992; OblSelVodKhoz, 2004); Crop water requirements based on recommendations of UzNIIKh (1992) and MAWR (2001).

stations (Fig. 3b) provided both the actual measurements and MERRA estimates. On the basis of the strong relationship between these datasets, with a 0.73 coefficient of determination (R^2; Fig. 3b), the MERRA estimates of the other two stations were also considered in the analysis. They allowed for filling in some blanks in the empirical measurements based on the nearest rainfall station observations and/or MERRA data estimates. The point measurements of the rainfall data were interpolated with a grid resolution of 250 m by using the kriging method.

3.2.2. Irrigation

Previously developed annual land-use maps showing cropping patterns of cotton, wheat, rice, intra-annual cropping sequences of wheat followed by rice (wheat + rice) or wheat followed by other crops (wheat + others) during 2003–2009 (Conrad et al., 2016) were used to produce the irrigation maps. The surface water applications to crops were estimated on the basis of local standards for irrigation requirements for different months and crops (Tables 2 and 3).

For example, the rice land-use class was assigned 26,200 m^3 ha^{-1} of seasonal water supply (Table 3), and its monthly water requirement (6820 m^3 ha^{-1} for July) was calculated by considering the cropping calendar and irrigation schedule during the growing season. A similar procedure was applied to the other land-use classes. Next, the volume of water applied per pixel cell was estimated as follows:

$$Irrigation\ per\ pixel\ cell\ [mm] = \{Irrigation\ rate\ [m^3ha^{-1}]\ \times Area\ [ha]\} \times \frac{1}{number\ of\ pixel\ cells}/1000 \quad (1)$$

The irrigation requirements for the hydro-module zones prevalent in Khorezm were averaged to derive the crop water requirements for the entire region. This generalization was justified given the small difference in water requirements among these hydro-module zones (Table 3), and it facilitated the procedure of allocating water amounts to a particular land-use type. When selecting the appropriate level of irrigation network efficiency (%) for the analysis, the following studies in the study region were considered: ponding tests in typical canal reaches of a Water Consumers Association (76%; Awan et al., 2011a,b), assessment of the main canals' efficiency (90%; Awan et al., 2011c), assessment of a sub-unit and nearly entire irrigation system efficiency (65–70%; Conrad et al., 2013), and FAO Aquastat database (63%; www.fao.org/nr/water/aquastat/countries_regions/UZB/index.stm). Eventually, the most conservative estimate (63%) was applied in our analysis because of the particular focus on marginal croplands, where the canal efficiency is considered to be the lowest. The estimation of actual water application was based on the crop-specific recommended water supply for irrigation and the conveyance losses in irrigation canals (Table 3).

By using Equation (1), the crop-specific irrigation requirements at monthly time steps were estimated and were assigned to all crops grown. The land-use maps between 2003 and 2009 were converted to irrigation water supply maps for April and July of each year. Because the land-use under specific crops changes annually, the resulting monthly irrigation water supply maps varied spatially and temporally between 2003 and 2009.

3.2.3. Actual evapotranspiration

The Surface Energy Balance Algorithm for Land (SEBAL) was used to estimate AET through a series of steps used to derive net surface radiation, soil heat flux, and sensible heat flux to the air using data from satellite imagery (Bastiaanssen et al., 2005). The basic remote sensing parameters used comprised Land Surface Temperature, Normalized Difference Vegetation Index, and Leaf Area Index. The meteorological information included wind speed, precipitation, solar radiation, air temperature, and relative humidity. The SEBAL model allows for estimating the instantaneous ET (ET_{inst}), which is the AET at the overpass time of the satellite, at each pixel location, i.e., at fixed regular distance intervals depending on the spatial resolution of the satellite data.

In this study, monthly AET maps at 1 km × 1 km spatial grid resolution were adopted from Knöfel (2016). These datasets were modelled with SEBAL based on the MODIS time series of 2003–2009. For transferring ET_{inst} to daily AET or monthly values, ET_{ref} was utilized under the assumption that the instantaneous evaporative fraction (ET_{inst}/ET_{ref}) was approximately constant for the day under observation. ET_{ref} was calculated on the basis of meteorological data and the daily sum of the half-hourly ET_{ref}, and the ET_{inst}/ET_{ref} fractions were used to estimate the daily AET. Validation of these estimates for Khorezm resulted in $R^2 = 0.55$ and a root–mean–square error (RMSE) of 1.72 mm day^{-1} based on a comparison with quality controlled eddy covariance measurements for the years 2009–2011 (Knöfel, 2016). These results agree with Conrad et al. (2007), who reported an accuracy of $R^2 = 0.55$ based on Class A evaporation pan estimates in Khorezm for 2004–2005. The results were resampled to 250 m resolution by using the nearest neighbor method.

3.3. Marginal cropland

The marginal cropland map developed by Fritsch et al. (2014) served as a proxy of the total cropland area of low productivity considered for retirement from annual irrigated cropping in favor of afforestation. On the basis of multi-criteria assessment, Fritsch et al. (2014) has postulated that 25% of the agricultural area in Khorezm, occurring mostly in the southwestern part of the region, is to a various degree marginally suitable for crop production. Of this assessment, "slightly marginal" croplands were dominant; however, "moderately marginal" and "marginal" classes together covered about the same area as "slightly marginal".

4. Results

4.1. Cell-based regional water balance

During 2003–2009, spatial patterns were observable for the rainfall distribution in Khorezm in April and July. The northern part of the region, which is bordered by the Amudarya River, received more rainfall than the southern part bordered by the Karakum Desert (Fig. 4b). However, the overall scanty rainfall did not influence the spatial distribution of the irrigation water in April (Fig. 4a), which ranged from 0 to 256 mm. In contrast, the irrigation water supply in July, ranging between 0 and 682 mm (data not shown), was higher in areas flanking the Amudarya owing to rice cultivation.

Consequently, the total water gain comprised of irrigation and rainfall inputs ranged from 13 to 274 mm. The April AET was only 0–35 mm in the desert and urban areas, which have negligible cropping

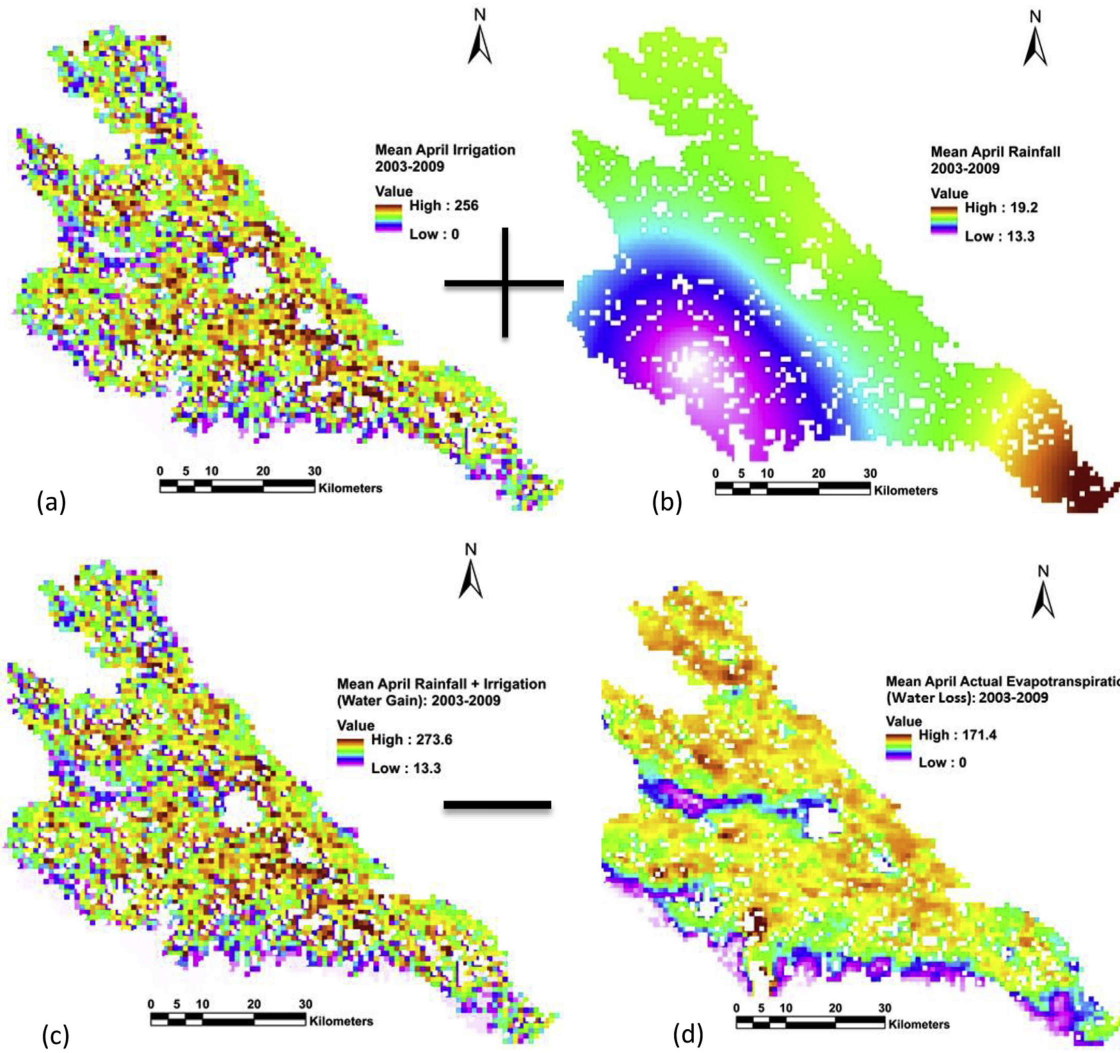

Fig. 4. Mean monthly amounts (mm) of (a) irrigation, (b) rainfall, (c) water gain, and (d) actual evapotranspiration in April estimated for the period 2003–2009 in the Khorezm region, Uzbekistan.

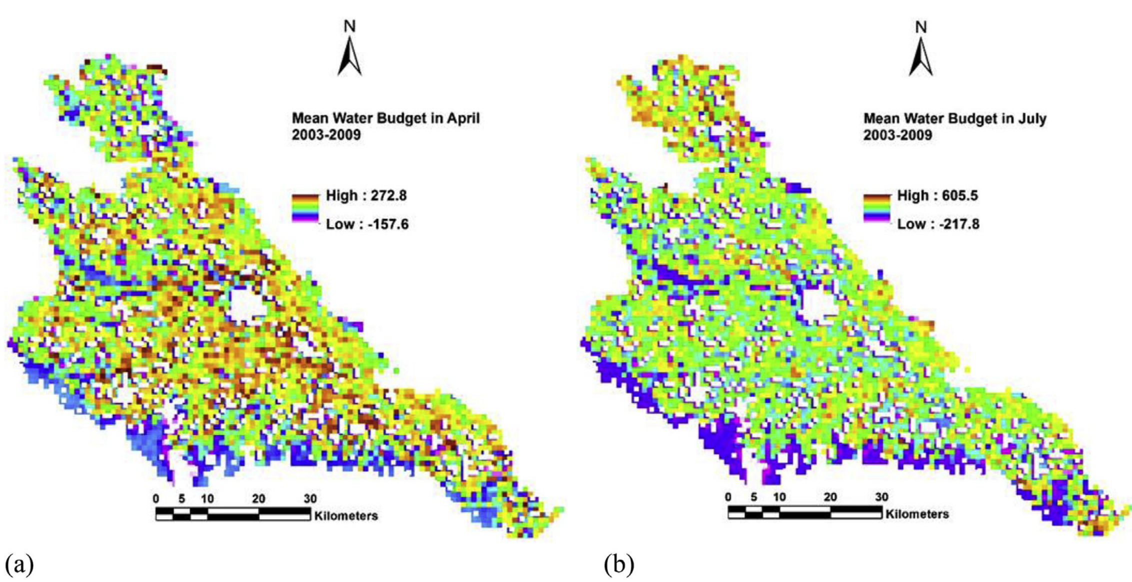

Fig. 5. Mean monthly water availability (mm) in (a) April and (b) July estimated for the period 2003–2009 in the Khorezm region, Uzbekistan.

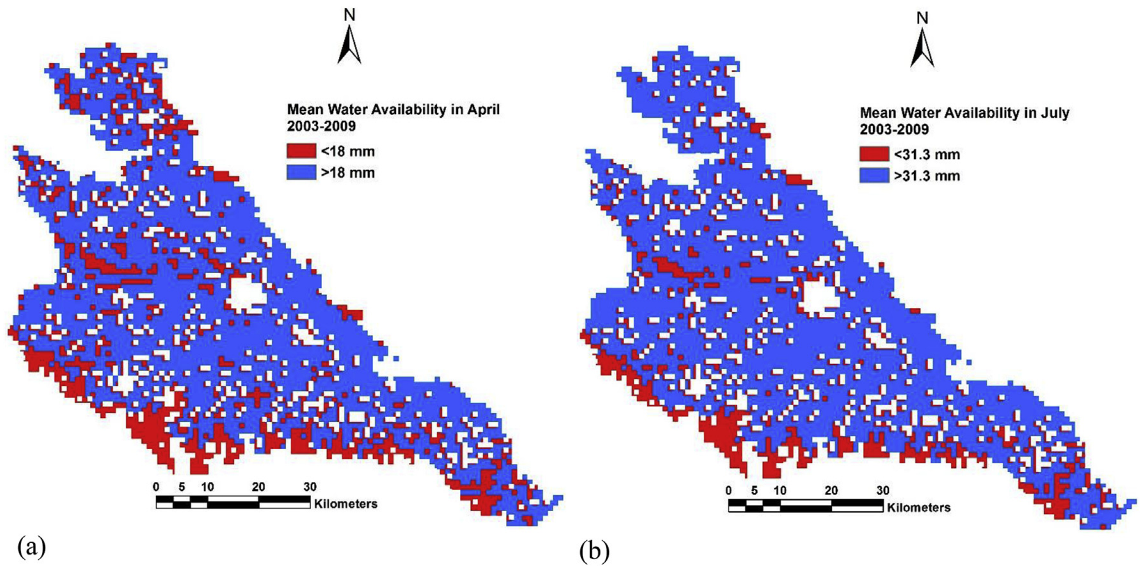

Fig. 6. Spatial distribution of sites with sufficient surface water available for satisfying the initial irrigation demand of afforestation in (a) April and (b) July estimated for the period 2003–2009 in the Khorezm region, Uzbekistan.

areas; however, it reached 171 mm in the irrigated areas, with a monthly mean of 68 ± 41 mm (Fig. 4d). In July (data not shown), the AET varied from 0 to 224 mm, with a monthly mean of 101 ± 59 mm. The increased AET in July is attributed mainly to increased vegetation cover of predominantly cotton during mid-season vegetation phases. Considering all of the factors stated above, the monthly spatial water balance for crops (i.e., the actual available amount of water in millimeters per 250 m × 250 m pixel cell) in Khorezm ranged from −158 mm to 273 mm in April and from −217 mm to 606 mm in July (Fig. 5a and b), in which the negative and positive values reveal water deficit and availability, respectively.

4.2. Spatial water availability for afforestation

Considering the irrigation requirement for supporting tree growth in the beginning and middle of the first growing season after planting (Table 1), about 69% and 76% of the marginal cropland area in Khorezm was characterized by sufficient water availability in April and July, respectively (Fig. 6a and b). As a result, the areas fulfilling both requirements constituted 67% of the marginal cropland area, which is approximately 17% of the total study area in Khorezm according to the time series of 2003–2009 (Table 4).

An overlay of the maps of marginal croplands (Fritsch et al., 2014) and of water availability for afforestation (Fig. 6a and b) revealed areas characterized by a productivity decline under current cropping practices, but having sufficient water available for afforestation activities (Fig. 7). Approximately 663 km^2 of the marginal croplands may be converted to tree plantations with priority given to areas characterized as least productive (moderately to highly marginal) under current cropping, or 42% of the marginal cropland area (Table 4).

Table 4
Areal statistics of marginal cropland suitability for tree plantation in the Khorezm region, Uzbekistan.

Marginal croplands classes suitable for afforestation	Area (km^2)	% of total marginal cropland	% of total area in Khorezm
Slightly marginal	250.9	25.4	6.3
Moderately marginal	327.1	33.1	8.2
Marginal	81.4	8.2	2.0
Highly marginal	3.6	0.4	0.1
Overall	663	67.1	16.6

5. Discussion

5.1. Hydrological aspects in afforestation planning

Field-scale afforestation trials (Khamzina et al., 2009; Schachtsiek et al., 2014) and farm-scale economic analyses (Djanibekov and Khamzina, 2016) in Khorezm have determined that afforestation can be an environmentally and financially attractive land-use option for degraded croplands because it combines a diversified agricultural production, carbon sequestration, an improved soil health and minimizes the use of irrigation water. However, upscaling these recommendations for regional land-use planning in irrigated agriculture requires prior spatially explicit consideration of the available water supply and irrigation demand of the trees and crops. Our approach considers the supply and demand based on a seven-year time series of water balances at a moderate resolution with a pixel size of 6.25 ha, which is appropriate for guiding afforestation planning at a regional scale, given the average farm and field size (Djanibekov and Khamzina, 2016). An alternative approach developed for the introduction of *E. angustifolia* plantations in the study region (Dubovyk et al., 2016) integrates multiple indicators of water availability and quality such as the distance to canals and drains and the depth to the groundwater table but accounts for variability in the water supply at the administrative district level only. Despite these methodological differences, the total area estimated as suitable for afforestation, about 70% of degraded croplands, was similar in this and the proposed approach. The advantage of the proposed approach is that it more accurately considers the spatio-temporal dynamics of water availability and requires fewer data for spatially explicit representation of the land suitability determinants for tree planting.

Due to the relatively modest data demand, the presented grid-based approach might have a wider range of applications for optimizing the agricultural water use. For example, the results can be used for improving the irrigation water distribution (Awan et al., 2011b). In particular, the information on immense water surpluses and deficits revealed for multiple grid cells in July might guide spatially explicit decisions on reducing applications in overly irrigated sites while supplying irrigation to drought-prone croplands (Djanibekov and Khamzina, 2016). The high-temporal (monthly) frequency of estimates is also appropriate for irrigation management. When provided with data on the irrigation requirement of alternative crops, the developed approach may support the evaluation of crop diversification options

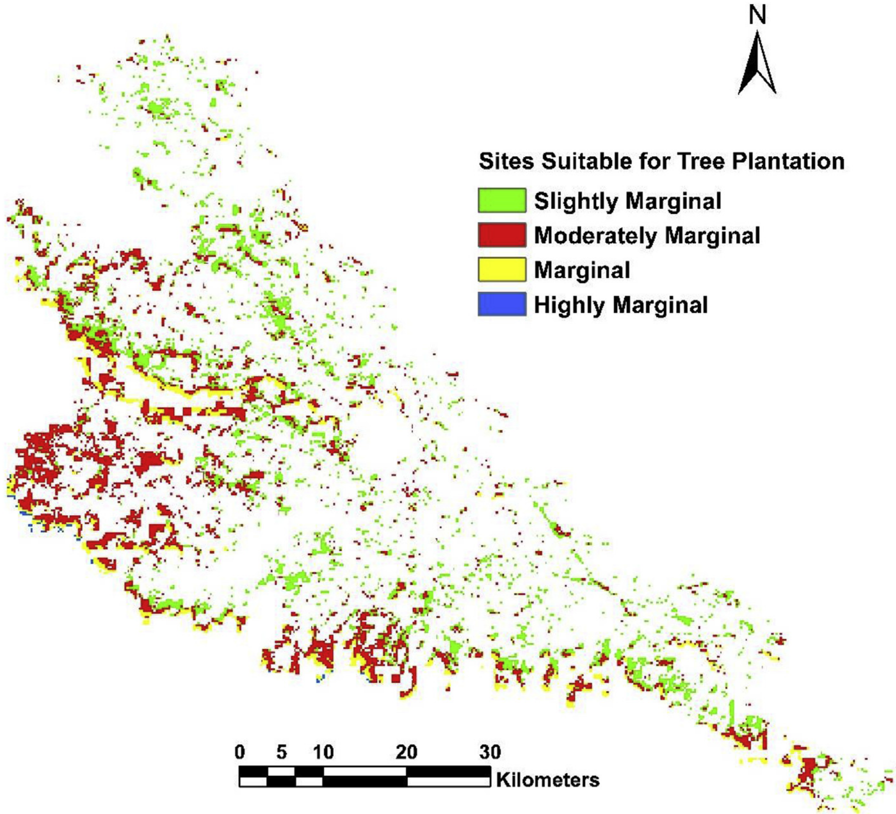

Fig. 7. Marginal croplands with sufficient water availability for afforestation considering the initial irrigation demand of trees averaging 15% of reference evapotranspiration.

(Bobojonov et al., 2013).

Further research should however include the hydrological components related to groundwater. In irrigated croplands of Khorezm, the groundwater regime is linked tightly to the irrigation input dynamics (Ibrakhimov et al., 2007), with a typical pattern of a relatively deep water table in winter and in drought years and shallow levels during pre-seasonal leaching and peak irrigation season. However, the significant (ground)water consumption by rapidly growing trees (> 1000 mm per season by 4-year-old stands) (Khamzina et al., 2009) in the long-run may result in a dramatic decline in the groundwater level and depletion of soil moisture, as reported for large-scale afforestation in arid regions of China (Cao et al., 2010). Increasing salinity under older tree plantations that rely solely on groundwater (Jackson et al., 2005; Khamzina et al., 2006) is another concern for the sustainability of dryland afforestation. Therefore, the groundwater component must be integrated in the hydrological modeling framework for simulating the long-term impacts of afforestation at different spatial scales.

5.2. Spatial hydrological modeling under conditions of scarce data

Our findings demonstrate a methodological approach that capitalizes on the available multi-source data for estimating spatially explicit water balances in irrigated regions within the ASB. Hydrological models require large volumes of high-quality data and are frequently limited by a scarcity or lack of input data of high quality, particularly in irrigated drylands (Li et al., 2009). This holds true for the ASB in general (Malsy et al., 2015) and for the study region in particular, where the spatial analysis of water balances is constrained by a poor infrastructure of meteorological observations and a lack of long-term datasets. However, rapidly evolving remote sensing technologies generate continuous and comprehensive information as input for hydrological models, which allows for simulation analyses in regions having scarce field data. Our study assessed AET and precipitation information based on remote sensing approaches and estimated the irrigation requirements by using MODIS-derived land-use data combined with locally recommended irrigation norms to compensate for the absence of discharge measurements at the field or pixel level.

It should be noted that the utilization of remote sensing introduced some uncertainty in the presented estimates. Given the classification accuracy of 80% for the land-use maps (Conrad et al., 2016), some pixels of cotton land, for example, might have been misinterpreted as fallow land leading to underestimation of the water supply. In addition, using only one meteorological station for calibrating and validating the SEBAL model to deduce AET might have introduced deviations, particularly at the desert fringes where extreme temperatures occur. Furthermore, downscaling SEBAL–AET estimates from 1 km to the 250 m grid generates uncertainty at the approximate occurrence of AET within the grid cell. Here, more elaborate methods such as that reported by Eswar et al. (2013) may be tested to overcome some of the limitations of the presented approach.

The limitations posed by field data scarcity remain with regard to the lack of field observations of actual water supply and distribution in croplands. Because they are based on local recommendations for irrigated crops, our irrigation supply estimates might be justified for years without a major drought, particularly for the predominant cotton and winter wheat crops grown under the state procurement system (Djanibekov and Khamzina, 2016). The recommended norms, however, are unlikely to be followed in years of severe water deficits such as occurred in the lower Amudarya region in 2000–2001 (Ibrakhimov et al., 2007).

6. Conclusions

The consideration of spatio-temporal dynamics of surface water availability in the lower Amudarya reaches allows for identifying degraded irrigated cropland sites suitable for conversion to agroforestry. To this end, remote sensing approaches are particularly useful in the absence of accurate field-based observations of water balance components, due to the general scarcity of spatial hydrological data in irrigated drylands of the ASB. The developed hydrological algorithm offers spatial guidance for afforestation efforts in degraded cropland areas because it explicitly considers the irrigation water availability for trees as a major determinant for the land-use change at the regional scale. The results show that much of the degraded cropland (67%) in the study region is likely to satisfy the initial irrigation demand of afforestation. For estimating the potential impacts of tree plantations on the regional water balance over longer terms, the developed analytical framework must include the groundwater component.

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